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IMPACT ON DESIGN WHEN INTRODUCING ADDITIVE MANUFACTURING IN SPACE APPLICATIONS

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Abstract

This paper studied how the introduction of additive manufacturing (AM) in space applications impacts the design phases. Together with three manufacturers of space applications, the potential benefit as well as constraints are studied to identify design gaps. A literature survey is conducted to match the needs and following an analysis the impact on design practice is formulated. Results show the need to combine a wider design exploration capability, in combination with comparative modelling strategies.

Keywords: additive manufacturing, design methodology, design analysis, engineering design

1. Introduction

Products designed for space applications such as launchers and satellite systems represent a challenging category of products from an engineering design perspective. Unlike other industries (Pawlicki, 2015), these products are produced in small batches and have to cope with the extreme conditions and requirements of launching and, at the same time, satellite applications have to be able to have a useful life of more than 15 years after successful orbit insertion. (Castet and Saleh, 2009). The recent advancements made in additive manufacturing (AM) technologies, are attractive for space applications. AM allows for weight and material volume minimization, which are indeed ideal drivers in costly products to be produced in low production volumes (Mellor et al., 2014). At the same time, AM increases the opportunity to apply novel strategies in the design activity. For instance, topology optimization combined with additive manufacturing (Brackett et al., 2011) offers the opportunity to manufacture products with minimal weight, by solving material distribution problems.

From a design perspective, however, AM represent a radically new way of manufacturing and brings a great deal of uncertainty. Engineering design strategies offer tactics for engineers to systematically guide the development of products (Cross, 2000). Such methods address the generation and application of technical knowledge to control and improve the product along its lifecycle. For example, design for manufacturing and assembly (DfMA) methods (Boothroyd et al., 2010) target the support of design products in such a way that they are easy to manufacture and assemble. However, regarding AM, the guidelines and strategies suggested by conventional 'design for X' (DfX) methods (Boothroyd et al., 2010) do not constitute a fully relevant design support. New guidelines and strategies on how to "design for additive manufacturing" (DfAM) are needed. Literature (e.g., Thompson et al., 2016) has provided a number of insights into DfAM but have often been derived from lessons learned from a number of industrial contexts - such as biomedical or automotive (Guo and Leu, 2013) - which do not present the same critical conditions such as the ones encountered by space applications.

This paper investigates the impact on design when introducing additive manufacturing in space applications. Through a literature and an empirical study, the restraints and challenges of space applications are matched together with the existing design strategies for additive manufacturing. The results of these studies are then discussed, pointing at the centrality of “modelling” as a crucial design strategy in the context of DfAM. This research was organized around the following research questions:

- *RQ1: How can DfAM methods be a support to effectively introduce additive manufacturing in space applications?*
- *RQ2: How can DfAM methods be extended to match the constraints imposed by the introduction of additive manufacturing in space applications?*

2. Research methodology

The study can be described as a Research Clarification (RC) in the Design Research Methodology (DRM) framework (Blessing and Chakrabarti, 2009). The research results come from the combination of a systematic literature mapping study (Kitchenham and Charters, 2007) and an empirical study in a Swedish-funded research project. The literature mapping was conducted by cross-analysing and ‘matching’ two neighbouring research areas – namely, research on design for additive manufacturing methods (DfAM domain), and research on the introduction of additive manufacturing in space products. The empirical study was realized in two workshops that joint the efforts of Swedish universities and aerospace industries with the objective of demonstrating the feasibility of introducing and qualifying additive manufacturing technologies in space applications.

2.1. Systematic literature mapping

A literature review on a topic identifies and evaluate existing areas or gaps demanding research (Wohlin, 2014; Alabama University, 2018). From the most popular methodologies for performing a literature review, systematic literature review and systematic literature mapping study, in this article a systematic literature mapping study was preferred. This methodology was preferred because it focuses on broad research questions reviewing substantial number of publications and aims for publication classification to achieve a high understanding of the research area (Barn et al., 2017). The literature mapping was performed on two sets of academic publications found in SCOPUS database, as it is the largest citation and abstract database of peer reviewed literature (Elsevier, 2018). The first SCOPUS search focused on research on DfAM methods and the second, instead, focused on research on AM applications in the space industry. As presented in Figure 1, the scope was limited to the subject area of engineering and to journal articles, conference papers and book chapters. Regarding the search conducted on the DfAM domain, the procedure was limited to title, abstracts and keywords and the results obtained were filtered by title, abstract and then by full-text content. Previous research (Bertoni et al., 2017) shows the importance of explicitly defining inclusion and exclusion criteria for filtering publications during literature reviews. The inclusion criteria, in this case, were to preserve entries related with the design methodologies applied to physical products (hence are related to the actual hardware, or mechanical, design) and that are intended to be fabricated using AM techniques.

Regarding the search conducted on the industrial application (space) domain, the search was limited to keywords, being then filtered by title, abstract and full text. The inclusion criteria were preserving entries related with the space industry and its implementation of AM, with a focus on the design of physical products with engineering content (hence related to the actual hardware design of a space product) and the used methodologies and encountered challenges during this process. For both searches, redundant items were removed and the remaining list was complemented with other entries implementing a procedure of backward snowballing (Wohlin, 2014) with the purpose of reaching publications outside the range of SCOPUS and increase the validity of the literature mapping. Finally, due to the rapid development of AM technologies, the final list was enhanced with not-peer reviewed new publications from the industrial/technology domain. The resultant list of articles is composed of 58 items.

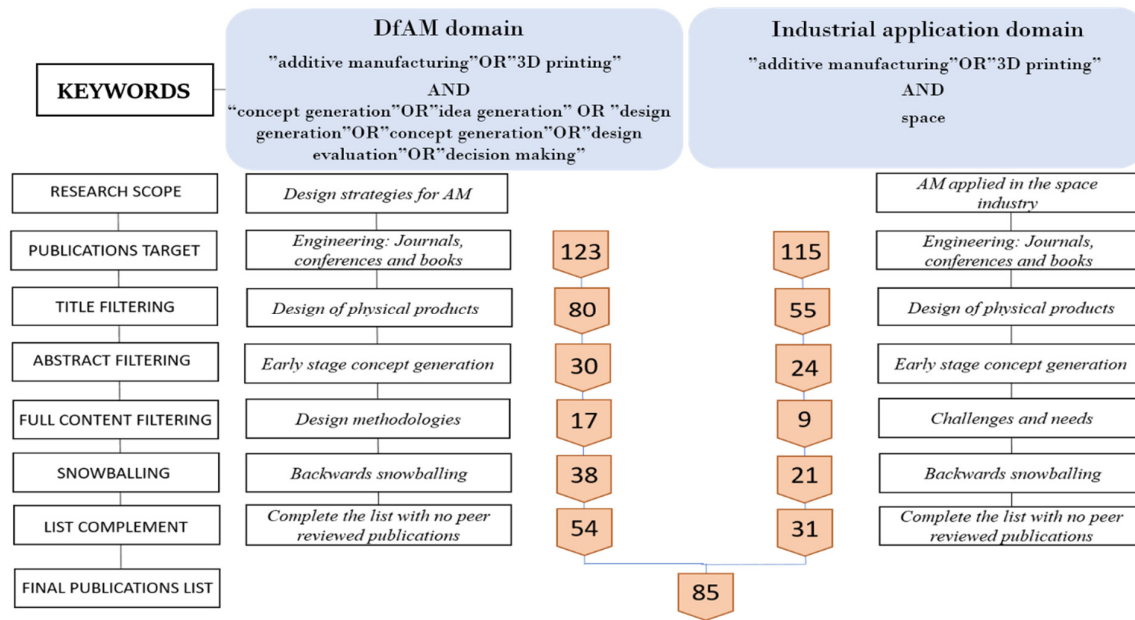


Figure 1. Systematic literature mapping procedure

2.2. Empirical study

Participants in the two workshops were industrial experts from three space equipment manufacturers, who are active in roles that relate to the generation and selection of new design concepts. The main aspects of interest during the workshop were related to two main dimensions:

- How AM enables the generation of new radical design concepts
- How AM engineering design phases have to be conducted, with a special emphasis on the qualification and certification stage

Problems in the current situations as well as wishes for the future were discussed. The workshop benefited from the collective analysis and idea generation on three case components presented by each of the company partners. The empirical data has been collected by observations using field notes and reflections, which were then distributed to the participants of the workshop discussion. Follow-up phone meetings were conducted with the participations for verification and exchange statements.

3. Research findings

This section presents the different results obtained from the two literature mapping studies performed, as well the findings from the empirical study conducted.

3.1. Literature mapping

On the first part of this chapter, the results from the mapping in the DfAM domain are presented. This part exhibits benefits, and constraints mentioned in the DfAM literature and tools and objectives found among DfAM methodologies. In the second part of this chapter, the results from AM applications in the space domain are presented and needs and challenges for AM in the context of space products are collected and explained. To wrap up, a cross analysis chart of both literature analyses is presented.

3.1.1. DfAM domain: Benefits and constraints from designing with additive manufacturing

From the DfAM domain search, a number of benefits and constraints emerged. The most recurrent benefit of AM is an unprecedented design freedom, 26 related articles were found, such as (Wits et al., 2013; Rosen, 2014; Laverne et al., 2015; Rias et al., 2017). This freedom enabled by 3D printing technologies includes shape, function, material and hierarchical complexity making possible product

customization (Rosen, 2013; Salonitis, 2016; EOS, 2018) without the need of tooling or increased manufacturing time and cost (Yang et al., 2016; Kannan, 2017). AM allows also the possibility of structural design (18 articles) (Thompson et al., 2016) enabling constructions with anisotropic materials, material gradient (Dimitrov et al., 2006; Gordon et al., 2016; Goehrke, 2017; Stratasys, 2018) and multiscale structures. Weight reduction is also an advantage, using strategies like topology optimization (Yang et al., 2016), or part consolidation (22 articles) in the form of integrated, internal or embedded designs and interlocking features (Gibson et al., 2010; Gutierrez et al., 2011; Cali et al., 2012; Davis et al., 2016; Advantech, 2017) facilitating assembly (Hague et al., 2003; Mahto and Sniderman, 2017). Constraints found related to AM include a constrained material availability (9 articles) (Thompson et al., 2016; Shao, 2017), performance and standardization of machines and processes (10 articles) (Laverne et al., 2015; Tilton et al., 2017; Stratasys, 2018) and CAD software adapted and developed for AM (13 articles) (Rosen, 2007; Salonitis, 2016; HSSMI, 2017; Käfer and Seit, 2017; Renishaw, 2018). Post processing is also a concern (19 articles) regarding the removal of support material, manufacturing tolerance limitations, releasing of thermal tension or improvement of surface finishing (Thomas, 2009; Klahn et al., 2015; Custompart, 2018; Hassanin et al., 2018). Another concern is feature size limitations (15 articles) like maximal angle between the part surface and the machine plate, that if surpassed creates the need of using support structure. Also, resolution of features, like graven fonts or maximum size of enclosed hollow volumes that, if exceeded will create the need of using internal support structure impossible to remove afterwards (Gordon et al., 2016; Kumke et al., 2016; Blösch-Paidosh and Shea, 2017; Kannan, 2017; Seepersad et al., 2017; MSCSoftware, 2018). Moreover, defects and their detection (10 articles) are problematic, as they can reduce fatigue life or facilitate crack propagation. There is a lack of knowledge of the physical phenomena that take place during the AM process and a difficulty to predict the quality of a piece (Ponche, 2013; MSCSoftware, 2018). Parts manufactured with AM have a complex thermal history that involves repeated fusion, directional heat extraction, and rapid solidification (Frazier, 2014; Loughborough, 2018).

3.1.2. DfAM strategies

22 entries were found related to methodologies for DfAM, the objectives of those methodologies are: design guidelines for fostering innovation/ideation (41%), for achieving part optimization (efficiently allocation of material) (30%) and for achieving part consolidation through reduction of the amount of parts to assemble (29%). Moreover, on the analyzed entries, the main strategies used for achieving those objectives are function modelling (54%), geometrical modelling (43%) and mathematical/physical modelling (3%).

The guidelines to foster innovation are design methodologies focused mostly on taking advantage of AM's design freedom. For this purpose, is frequently used *function modelling* to decompose the product function in hierarchical sub functions implementing tools like the modular three-dimensional function graph presented by Boyard (2015). Other strategies combine function modelling with idea generation tools, like the use of databases or analogies (Emmelmann et al., 2011; Brandt et al., 2013; Rias et al., 2016). *Geometrical modelling* is also implemented through topology optimization (Maheshwaraa et al., 2011; Vayre et al., 2012; Panesar et al., 2014) and *mathematical/physical modelling*, especially for modelling material behavior through mathematical equations (Chen et al., 2016). Methodologies focusing on part optimization aim to achieve an optimized version of a design, allocating better the material to minimize the material amount used, reducing weight, building time and manufacturing cost (Yang et al., 2016; Hu et al., 2017). For this purpose, *function* (Boyard et al., 2013) and *geometrical modelling* (Ponche et al., 2012; Ponche, 2013; Ponche et al., 2014) are implemented. Part consolidation have the objective of reducing the amount of assembly parts of a design through function integration, this approach can reduce the overall assembly time and cost (Cali et al., 2012; Maidin et al., 2012; Yang et al., 2015; Essa et al., 2017) using function integration through *function modelling* (Yang et al., 2015). From the literature mapping of the DfAM domain, can be concluded that the main efforts are directed to the exploration of benefits and constraints of AM and their translation into methodologies for aiding the designer to achieve mostly innovative designs, part consolidation and part optimization. The focus seems to be directed to take advantage of AM design freedom, with little regard about the introduction of this technology into the industrial application sector.

3.1.3. Industrial application domain: Current focus of research on AM applications in space

Needs and challenges regarding the application of AM in the context of space products are presented in the left part of Figure 2. The main focus is set on the need of developing comparative modelling strategies to aid the process of qualification (Wang et al., 2008) and help ensuring quality (32%).

Qualification is needed for the establishment of a sufficient technology readiness level (Mankins, 1995), diminishing the level of uncertainty related with a new technology and is a need is present in all the extension of the production chain (Yeong et al., 2013; Gockel et al., 2014; Kim et al., 2014; Martukanitz et al., 2014; Uriondo et al., 2015; Farinia, 2018). Second, comes (17%) the need to develop methodologies for design (Goehrke, 2017), like the ones mentioned on the previous section, and thirdly, 14% corresponds to the need of clear set of rules for printing process set-ups. Printing set-ups refers to considerations to be made for starting the printing process, from choosing machine and materials to selecting printing direction. These set-ups affect properties like: thermal, electric conductivity, tensile and yield strength, surface roughness, part accuracy and the use of support (Zhang and Bernard, 2013; Clinton, 2016; Blösch-Paidosh and Shea, 2017).

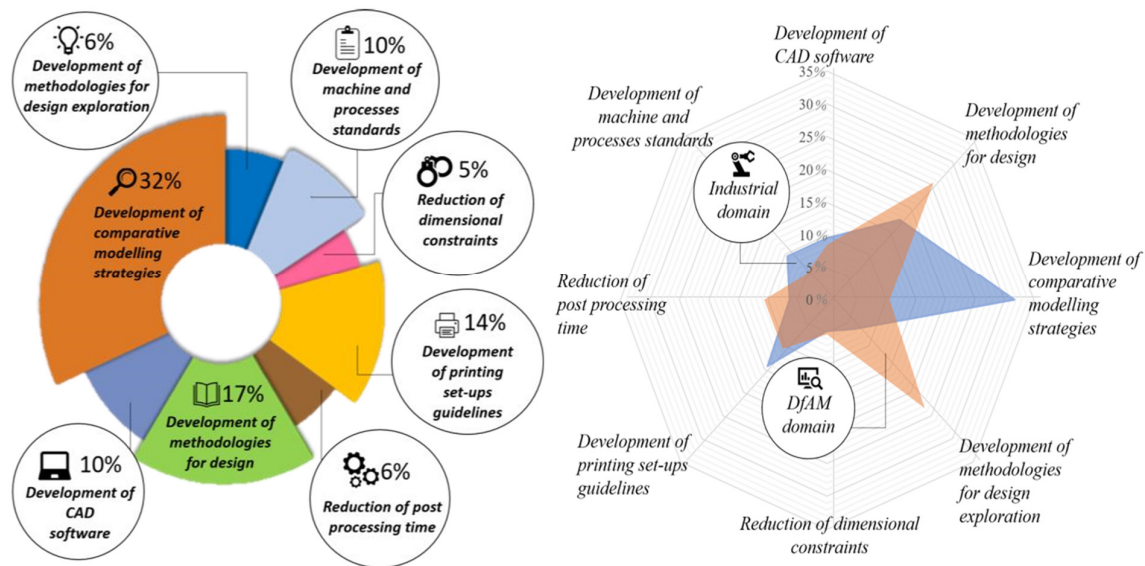


Figure 2. Left, needs and challenges to apply AM in space products; Right, comparison of needs and challenges from the industrial domain with challenges addressed in the DfAM domain

Machine processes and standards (10%) are also in need, as they help improving quality and qualification, as well as increasing market opportunities (Munguia et al., 2008; Johnston et al., 2014; TNO, 2014; Swerea, 2017; Kramer, 2018). Standards currently applied in traditional manufacturing are not suitable for AM technologies (Monzón et al., 2015). The need to develop or adapt CAD software to AM is also mentioned (10%) as traditional CAD tools for conventional manufacturing are obsolete. Furthermore, current CAD systems developed or adapted for AM are still in development (McClintock, 2017) and there are few CAD packages for helping the engineers to fully adopt AM (Dordlofva et al., 2016; McEleney, 2017; Hendley, 2018) and those packages have still limitations (Ghidini, 2013; Gibson et al., 2015; Yang and Zhao, 2015; McClintock, 2018). The need of methodologies for aiding design exploration and generating innovative ideas is also mentioned (6%), as well as the need to improve the technology to, for, example, diminish dimensional constraints (5%) and, the need to reduce post treatment (6%) recognized as a contributor for increasing lead time and cost (Schmelzle et al., 2015; Dordlofva et al., 2016; Grunewald, 2016; ESA, 2017; Hu et al., 2017; McClain, 2017; Schelmetic, 2017). A poor surface finish, for example, must be treated with complementary processes due to the negative effect it has on fatigue resistance, heat transfer or contact among internal surfaces (Kumbhar and Mulay, 2016; Lindwall et al., 2017; Martin-Iglesias et al., 2017).

For concluding this section, the right side of Figure 2 present the needs from the industrial application domain compared with the needs addressed in the DfAM domain. The areas of interest of the industrial and DfAM domain are misaligned, as the industrial domain seems primordialy interested on developing comparative modelling strategies and the DfAM domain, in developing methodologies for design exploration and methodologies for design.

3.2. Empirical study

The first phase was focused on design exploration, were the industrial partners presented products currently manufactured with traditional processes, with the intention to be redesign for AM. In that context, companies and academic partners shared their expertise with a brainstorming session and collaborated to create a variety of redesign concepts for the targeted products. It was observed in this phase a tendency to generate concepts similar to the preexisting ones and a difficulty to integrate the benefits and constraints of AM. The major manufacturing and qualification concerns expressed by the industrial partners are related with the nature and detection of defects, as well as their impact on performance, material behavior and capabilities, surface finishing and geometric accuracy. On the second phase, function modeling was implemented, the case-products were decomposed into hierarchical functions to help the design process and assist the process of qualification, qualifying features and geometry regarding their associated function and manufacturing restrictions.

Whilst the top-level functions from the original and the redesign models are expected to be the same, the constraints emerging from classical, often subtractive, manufacturing technologies can be relieved. Using this approach, the original functions and manufacturing constraints were identified, and the constraints emerging from traditional manufacturing were relieved. However, when conceptualizing the use of AM, benefits in geometrical freedom are realized, but there are also new constraints added. Introducing function modelling and constraints replacement in the workshops, enabled the discovery and removal of obsolete functions, the better realization of the existing ones and the possibility to include new. Figure 3 shows an example about the redesign of an annulus profile. In the example, an annulus shape manufactured with traditional methodologies is redesign for AM. In Figure 3 (left) the annulus is printed without redesign and the diameter is larger than a maximum diameter threshold for avoiding the need for support structures (AM constrain). Hence, the annulus requires the use of support structures. Considering this constrain since the early design allows for a new design that reduces the use of support (Figure 3, right).

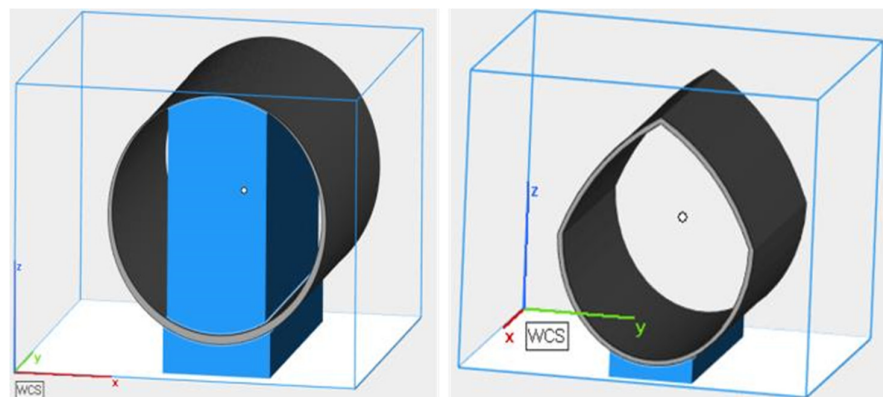


Figure 3. Annulus profile example elaborated using Materialise® Magics constraints replacement when designing with AM leading to geometry transformation to avoid undesired support structures

4. Discussion: The need for a novel modelling strategy to introduce AM in space applications

The results from the literature and the empirical study suggest that for AM to be introduced in space applications, the parts should go through a process of redesign, to take full advantage of this technology

(Salonitis, 2016). However, the designing task in additive manufacturing is difficult as it involves a process of unlearning the design guidelines for traditional manufacture. For facilitating the design process, many DfAM methodologies are currently being developed and most of them (42% of the entries in the literature study) are focused on aiding the exploration of innovative design and more than half (54%) of the entries in the literature study focus on the adoption of *function modelling* to decompose the product function in hierarchical sub functions (Boyard, 2015), where new designs that fulfil the same (or new) functions can be generated through idea generation tools, like the use of databases or analogy methods - such as biomimicry (Emmelmann et al., 2011; Brandt et al., 2013; Rias et al., 2016).

Through the use of such DfAM methods radical new designs and geometries can be generated (for example, the annulus profile in Figure 3), but this introduces an element of novelty that challenges decision-making processes during the design activity. The industrial practitioners taking part in the empirical study elaborate on the fact that - when making decisions - novel design alternatives are always compared to a base reference design, where a solid experience and confidence exists. Novel designs need to be proven to be “better” in comparison with existing solutions. These decisions have to be made early (already on a concept level), where design changes can be made spending little time and effort. The downside of making decisions early is that the full set of information may not be available at these stages. Practitioners hence stress the need in the early design phases to generate information and knowledge about the “goodness” of such new designs for AM, in comparison to existing solutions. This need is mapped also in the results of the literature study, where research on AM introduction in space application stress the interest for *comparative modelling strategies* (32% of the entries) and sets little attention on design exploration (6%) (Figure 2, right).

This discussion suggests the importance of *modelling* in order to exploit both design exploration opportunity and confidence in decision making. From the results of the literature analysis two main trends for modelling strategies emerge. Function modelling allows to represent current as well as novel designs simultaneously. Yet, to allow full comparison in the context of AM for space applications, manufacturing constraints should also be represented in a function model. In this way, constraints can be removed and introduced, allowing the generation of new insights in the design process already from the early phases. These types of representation could also become input to other comparative modelling strategies, such as the identification of critical ‘features’ to be tested in a physical artefact (intended to act as a ‘qualificator’) where critical design properties – regarding for example quality, surface finishing, or fatigue life – can be compared to existing solutions already since early design.

5. Conclusions

This paper studied how the introduction of additive manufacturing (AM) in space applications impacts the design phases, combining a literature and an empirical study in collaboration with three manufacturers.

- The literature review indicates that - at present - focus is dominated by 1) the need to understand current constraints and behaviour of AM, and 2) ways to benefit from the increased degrees of freedom using AM.
- Few studies are found on a systematic and generic modelling approach for DfAM. This need is instead stressed by industrial practitioners in the empirical study. Such a modelling approach can support the generation of insights and learnings that match the characteristics of AM with the design objectives/functions driving the novel designs.

Preliminary findings indicate that a modelling approach able to represent functionality and constraints linked to different product concepts is crucial for real world design cases. For further work, it is suggested to explore the modelling of functions and constraints when re-designing for AM.

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